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STUDY OF WING FLUTTER

Part II—CONTINUATION OF TESTS ON REVISED APPARATUS
AT WRIGHT FIELD WIND TUNNEL

(Supplement to Part I—Test of Apparatus and Discussion of Procedure
A. D. M. 1014, dated October 20, 1928)



(AIRPLANE BRANCH REPORT)



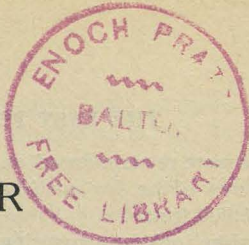
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STUDY OF WING FLUTTER

Part II.—Continuation of Tests on Revised Apparatus at Wright Field Wind Tunnel

(Supplement to Part I. Test of Apparatus and Discussion of Procedure, A.D.M. 1014, dated October 20, 1928)

(Prepared by Capt. C. F. Green and Dr. J. E. Younger, Matériel Division, Air Corps, Wright Field, Dayton, Ohio, April 2, 1930)

INTRODUCTION

Shortly after the war the appearance of undamped and destructive oscillations in cantilevered wings of certain monoplanes and in long unbraced overhanging portions of various biplane wings began to be recognized as a distinct dynamic manifestation independent largely of the actual strength properties of the wings. For some time the aileron was assumed to be the source of the disturbance inasmuch as most of the vibration and final disintegration was observed at this point. This conclusion was true in many cases, but with the appearance of vibration in certain fully cantilevered wings it became apparent that it was possible to set up strong undamped oscillations in the wing—entirely independent of the aileron. It was later found that the participation of the aileron in this action might be of any degree, dependent largely on the balance, rigidity, and hook-up of the aileron itself. This is borne out and amplified in this report.

The list of references contained in the body of the report refers chiefly to experimental work of both a theoretical and experimental nature. A history, or compilation, of the many examples of actual flutter encountered in flying does not appear to be necessary in this report. There is presented, however, in the following pages the account of one clear-cut and illustrative case. This (the "Arc-en-Ciel") is quoted for the reason that it contains first-hand evidence of the pilot—a class of evidence not ordinarily obtainable in cases where an undamped and destructive flutter has been well established.

CRASH OF AIRPLANE "ARC-EN-CIEL."—(From *Monthly Information Bulletin*, October, 1928.) Office of Naval Intelligence, U. S. N.

The "aerodynamic" phenomenon, said by experts to have caused the fatal crash of the airplane *Arc-en-Ciel*, and the subsequent death of its pilot and mechanic, was partially explained by the engineer, Gianolli, after he regained consciousness.

An accident is a terrible thing. At the same time, there is some consolation in knowing that certain accidents afford information, which, if taken into account, may be of service to the progress of aviation. This

seems to be the case with the distressing accident at Orly. Mr. Maurice Victor gives below a thesis based upon facts which render his article of real interest:

"The terrible accident to the *Arc-en-Ciel* brings to the front the problem of present-day technique concerning wing vibration.

"By examining the last moments preceding the accident, it is possible to reconstitute various phases and endeavor to draw lessons therefrom.

"As one knows, the Couzinet monoplane was fitted in the first instance with three 180-horsepower Hispano engines, and under these conditions flew for about 5 hours 30 minutes.

PREVIOUS TESTS

"With the object of diminishing the weight per horsepower by raising the power, to increase security by allowing flight with the central engine alone, and also with the idea of facilitating taking-off when departing for America, the central 180-horsepower engine was replaced by another engine of the same make, but of 500 horsepower. After this modification the *Arc-en-Ciel* carried out tests during a total period of 6 hours and 30 minutes.

"These tests proved very satisfactory, for, although carrying a load of 6 tons, the plane took off after about a 175-foot run.

"A program of tests was mapped out covering handling trials, consumption, and speed tests, as well as a long flight of about 10 hours and a climb to 5,000 feet.

"The handling trials were most satisfactory, Drouhin being able to take his hands off the controls with the three engines throttled at 1,600 revolutions. In addition, by checking either of the lateral engines, Drouhin was able to abandon the rudder bar and swing the plane with ease either to the right or left.

"Speed tests, carried out over a 2-mile course, gave an approximate speed of 135 to 145 miles per hour. Evidently these figures are not as exact as those obtained with the Dumanois-Ceccaldi automatic speedometer, but the constructors of the Couzinet machine, which was a purely private plane, had to be content with these rough calculations.

"Following the two speed tests on August 6, a bad leak in the left radiator had to be repaired.

THE LAST FLIGHT

"Tests were recommenced on Wednesday, August 8, and the crew of the *Arc-en-Ciel* decided upon a climbing trial to 5,000 feet.

"Drouhin took a registering barograph with him; Gianolli, lanet, and Manuel got on board. Couzinet stayed on the ground with a deputation of the ex-students of Arts and Crafts Society, who had come to watch the flight; Le Brix, who arrived late, missed the departure.

"After a perfect take-off Drouhin made several turns in order to demonstrate the easy handling of the machine, and, after turning over the airship hangar, went off in a direction parallel with the Paris main road. The machine was then at about 300 feet altitude.

"Drouhin opened out all three engines, and the machine gathered speed while dropping slightly and arrived in front of the S. N. Ae hangars—used for planes calling at Orly—at a speed of 150 to 160 miles an hour and an altitude of about 1,000 feet. This estimate of the speed is the rough guess of witnesses and has only comparative value. Nevertheless, all those who saw the plane agree concerning the very great speed attained.

"At this moment the accident commenced, and the following is an account given by Drouhin the same night as soon as he had strength enough to speak, on his deathbed:

"A few seconds after passing over the airport offices the left aileron began to vibrate. Seeing the danger, Drouhin closed the throttles and tilted up the plane slightly in order to brake. The vibrations then became general throughout the machine, being as much as 5 feet at the extremities of the wings. The body of the machine vibrated with extreme rapidity, and the trepidation affected the controls to such an extent that Drouhin was no longer master of the plane. No longer able to hold the wheel, Drouhin found the machine developing a very great speed, which went into a vertical spin with such a noise—caused by the vibrations—that the roar of the throttled engines was completely drowned.

"The plane stood up to this and nothing gave way. At the height of its spin it got on to an even keel at about 200 feet height. After heistating a fraction of a second, the *Arc-en-Ciel* made a nose dive and dropped, regaining speed at an angle of 40° to 50°. Drouhin having once more obtained control, endeavored to correct the descent of the machine—which was falling toward the point where the Fontainebleau and Orly roads cross in order to avoid a group of people and cars that had gathered at that spot. The controls answering to his movements, Drouhin swung to the right and endeavored to flatten out at an angle of 20°. Unfortunately, the machine was too low and the right wing struck the ground during the turn. Then followed the catastrophe."

THE VIBRATION PROBLEM

"The first cause of the accident must be sought in the vibration of the wings which Drouhin tried to check by throttling down and rising slightly. The accident was caused by loss of flying speed.

"Numerous hypotheses have been put forth, among them being the following, which may be immediately refuted—that the machine was constructed of 'odds and ends.' No, the machine was very well constructed and very solid, even more so than revealed by calculations. Proof of this is shown by the wonderful way in which the wing fabric held up under the strain of such terrific vibrations, calling for enormous structural resistance.

"Destruction by loss of speed is unhappily too well known, and its cause is known. In order to avoid this it is absolutely necessary to face the question of efficient control at low speeds.

"In this connection one might indicate the great profit to be obtained by the study of a force independent of the speed in order to 'trim' a machine in danger. Rockets, arranged at the extremities of the wings and fired by a simple electric contact, reacting with the entire leverage of the wing fabric, might provide a means of saving life in extremis.

"There remains the question of vibrations of the wings. According to what is already known of this aerodynamic phenomenon, it appears that at a certain speed, always greater than the normal speed of the machine, the ailerons take on an oscillatory movement which spreads to the wing fabric, but becoming much greater, and continuing until either a breakage takes place or speed is reduced to diminish the movement.

"Following on five accidents that occurred to British machines through nose dives at 260 kilometers an hour, a commission of inquiry went into this question of vibration.

"It was ascertained that, at the above-mentioned speed, violent vibrations—from 800 to 1,000 per minute—occurred at the extremities of the wings. The examination of the machines revealed broken struts, aileron control levers torn out, considerable disorder of the interior stay wires, and the beginnings of breakage of longitudinal parts.

"Other English accidents have shown that vibrations may begin in the body of the plane, and also, in one case, in the rudder.

"In France two other examples are furnished by Albert monoplanes which took part in an economical plane contest at Orly, piloted by Descamps and Thoret. The wings of these machines began to vibrate violently during the speed test, but the matter was not treated as of great importance, for the pilots stopped these oscillations by throttling down.

"What is the cause of these wing vibrations? The following is an hypothesis taken from No. 13 of *Le Document Aeronautique*, put forward by Mr. Sayers, the technical collaborator of our London confrere, The Aeroplane.

The cause of vibrations

"A wing is composed of a fixed part containing the resisting structure, and a movable part, the aileron. If this wing, either by a puff of wind or by the control, is animated with an upward movement, the aileron will be obliged to follow this movement. However, in view of the position of its center of gravity behind the hinge and the play existing in the controls, this aileron,

by inertia, will follow the general movement of the wing with a certain delay, being projected downward with regard to the wing, and the incidence of the wing fabric will increase, augmenting still further the sustentation.

"The upward movement will stop as soon as the elastic forces of the structure observe this passing effort, but the aileron, always late through its inertia, will pass this position, rise with regard to the wing, while considerably diminishing the sustentation of the wing fabric. This reversing of efforts joined to the energy stored up in the structure will project the whole wing downward again, the ailerons being always late, and an oscillatory movement will have set in.

"It must be admitted that this movement may also be caused by whirlwinds set up by the rush of air at high speeds. The shallow ailerons are in this instance the center of these whirlwinds which bring about vibratory movements by a process analogous to that described above. Once the wing starts to vibrate, it is very difficult to know what may follow, on the one hand from the inertia of the structure, and on the other from the inertia of the aileron.

"In some cases, resonance phenomena become evident and amplify the vibrations until there is a complete breakage, no matter what may be the coefficient of the strength of the wing fabric. In others, on the contrary, a slowing down is possible and vibrations may take place without damage.

THE REMEDY FOR VIBRATIONS

"From the foregoing, it is quite evident that in order to overcome vibrations of the wing fabric it is first necessary to deal with the aileron by diminishing its weight, and consequently its inertia; by eliminating its disturbing tendency by coinciding the center of gravity with the hinge; by increasing the rigidity of the controls so as to keep it in a fixed position with regard to the wing. It appears to be certain that the latter operation should be very effective in eliminating wing-fabric vibrations. This was the means adopted in order to correct this annoying tendency in the Albert monoplanes. One must also admit that warping movements either by pulling or compressing on the wires or tubes transmits displacements to the ailerons owing to the deformity of the wing fabric—and hence the vibration—and that a twisting control, at the end of the aileron, will do away with this risk.

"On the other hand, it is possible to increase the rigidity of the wings, particularly at the extremities, so as to act at the moment of inertia and the period of vibration.

"The question must be looked at from yet another angle, viz, the resistance to vibrations offered by monoplanes and biplanes either with indirectly supported or wire-rigged wings.

"An indirectly supported wing submitted to vibrations behaves like a leaf spring and bends through a considerable arc without breaking. The example offered by the Couzinet and Albert planes in this connection is striking. Their two wooden wings have stood up well to vibrations.

"Does metallic construction, also for indirectly supported wings, offer the same advantages? It would be presumptuous to reply in the affirmative without backing up the statement by figures. A careful study of the question would be necessary in order to elucidate this important point. However, it appears that metallic construction does not allow great flexes and offers more rigidity. It does not permit the ailerons to take on large movements and should lead to the suppression of vibrations. This is only a simple opinion and is given under all reserve.

"The wire-rigged wing, at first sight, would seem to resist vibrations better, but is this not a deceptive appearance, and ought not we to put down to vibrations started by the ailerons such resounding accidents as those of Latapie and Brager? If one admits that vibratory movements can start, that resonance phenomena can exist, there is no doubt that, when these vibrations become evident during a flight and the pilot will not reduce speed in order to overcome them, some part of the machine is bound to break, no matter how solid it may be.

"The mast attachment seems to be the part to give way. This declaration is in no way a criticism of a whole family of good machines, but an argument backing up an hypothesis that, in the domain of electricity, led to the coming of wireless.

"Other examples might be quoted. Why, in certain biplanes, do the rigging wires break in the region of the ailerons? Vibration and resonance! In spite of replacing cable axes by swivel articulations, breakage still occurs just so often as the period of vibration of the wing fabric is not in resonance with that of the ailerons. In wire-rigged machines—biplanes or monoplanes—the vibrations have less amplitude and are of less importance than those occurring on unwired wings. Nevertheless, they still exist and are none the less dangerous, but rather to the contrary.

"It is very easy to criticize the resistance of materials for strains for which they have not been designed. It is also most convenient to place at the door of metallurgy and thermic treatment the unexplained breakages. The truth is at the side, in the vibrations.

"In September, 1927, a Dornier-Markur of the *Lufthansa*, with the German ambassador on board, lost a wing in the air, breakage of the iron mast fitting by vibration. Other machines of the same type have flown for a long time without any accident. Why? Without doubt because the warping control has had a certain amount of play and the flappings of the ailerons have encountered resonance.

"The problem is important and difficult to study, because there are no precise data for these complex calculations. It may perhaps be possible to carry out tests with models in the wind tunnel, the models being fitted with wings of which the moments of inertia will be the function of the coefficient of reduction.

"Whatever may be the principle of the test adopted, it is evident that we must go into this question in real earnest if we do not wish to have a recurrence of accidents before which, too often, technicians avow themselves to be powerless."

AIRFOIL FLUTTER INVESTIGATION

SCOPE OF INVESTIGATION

This investigation is a continuation of a series of experiments initiated by the authors¹ for determining the influence of the physical characteristics of an airfoil on its tendency to flutter in an air stream.

In this series of experiments, the following characteristics were investigated:

1. The extent to which the aileron participates in the action of flutter.
2. The effect of variation of the natural torsional period of the wing.
3. The effect of the camber of an airfoil on the critical velocity at which flutter is precipitated.
4. The effect of the location of the elastic axis.
5. The effect of the distribution of the mass of the airfoil.
6. The effect of the size of the airfoil.

APPARATUS

The investigation was carried out in the Wright Field (formerly the McCook Field) 5-foot wind tunnel, a description of which may be found in Serial Reports No. 1810 and No. 3082. The wing-flutter test apparatus is the same as that described in Air Corps Information Circular No. 635, with the exception that the bearings are made frictionless by supporting the shaft as shown in Figure 1, and a graphical frequency recording device, shown in Figure 2, is added. The airfoils were constructed of 0.032 duralumin sheet formed over spruce bulkheads.

1. THE EXTENT TO WHICH THE AILERON PARTICIPATES IN THE ACTION OF FLUTTER

It should be noted before entering into the discussion of the results of these experiments that airfoil flutter may be divided into two classes; namely, (a) aileron flutter, and (b) torsional flutter. Aileron flutter is the result of a condition of resonant oscillations between the aileron and the wing, and as noted in the previously mentioned reports by the authors exists practically as a pure bending motion. Numerous experiments conducted by the authors on this type of flutter confirm the conclusions of the original investigations² that a statically balanced aileron can not precipitate aileron flutter. Most disasters in aviation traceable to wing flutter are probably caused by the aileron type of flutter.

Torsional flutter, which is the principal subject of this report, may exist with or without an aileron, and is not in general influenced by the action of an aileron. This type of flutter may exist in a monoplane wing or

in the blade of a propeller, and appears to be the prevalent type of propeller flutter. The authors have not found it possible to develop a flutter in bending without the aid of an aileron.

During the course of the investigation, a series of slow-motion pictures were taken of certain runs which involved full participation of the aileron. The extremely clear cut nature of this pictured action verifies the conclusions set forth above. A description of the pictures taken of the aileron action as well as other pictures of high and low incidence flutter will be published in the form of an appendix to this report.

2. THE EFFECT OF VARIATION OF THE NATURAL TORSIONAL PERIOD OF THE WING

Throughout this present investigation and in verification of the results of previous tests,³ it has been found that, other conditions remaining fixed, the air speed at which flutter can be precipitated varies substantially as the frequency of the natural torsional period of the wing. This lends verification to the belief that true destructive flutter requires resonance between the natural period of the wing structure and the aerodynamic torsional impulses created by a flow of air of sufficient velocity around the airfoil section.

The most important conclusion, therefore, in considering the prevention of undamped flutter is that wings intended for high speed or severe maneuvering must be made torsionally rigid in proportion chiefly to the diving speed which they may be expected to withstand. This torsional rigidity must be considered as a requirement related to but not necessarily dependent on the ordinary strength characteristics of the wing.

3. THE EFFECT OF THE CAMBER OF AN AIRFOIL ON THE CRITICAL VELOCITY AT WHICH FLUTTER IS PRECIPITATED

In studying the effect of the camber of an airfoil on the critical velocity at which flutter is precipitated five nontapered airfoil sections were used, as follows:

(1) An airfoil with a contour similar to that of the root section of the U. S. A. 35, commonly designated as the U. S. A. 35-A. This is a thick airfoil section with a lower surface which is almost flat.

(2) An airfoil with cross section similar to that of the root section of the N. A. C. A. No. 81. This is a thick airfoil section with the lower surface cambered in the opposite direction to the upper surface. This airfoil thus approaches a symmetrical streamlined section.

(3) An airfoil with the Clark Y section. This is a relatively thin airfoil section.

(4) An airfoil with the N. A. C. A. M-6 section. This is a thin airfoil section with a stable center of pressure.

(5) A thin airfoil with a perfectly symmetrical streamlined section.

¹ See, Study of Wing Flutter, Air Corps Information Circular No. 635, and Wing Flutter Investigation on Brady's Wind Tunnel Model, Air Corps Information Circular No. 608.

² See, Remarks on the Stability of Oscillation of an Aeroplane Wing, by A. G. von Baumhauer and C. Koenig. Translation for International Air Congress, London, 1923.

³ See Air Corps Information Circular No. 635.

Previous experiments⁴ show that, in general, an airfoil will flutter at any angle of attack, but that there are two minimum velocities at which flutter may be precipitated, namely, at some angle of attack at or near the angle of zero lift, and at some angle of attack at or near the burble point. The velocities required to precipitate flutter at these two particular angles of attack were shown to be very much lower than the wind velocities required to precipitate flutter at any other angle of attack. These investigations were accordingly carried out at angles of attack near the angle of zero lift and near the burble point for each airfoil at the particular angle of attack which would give the minimum velocity in each position at which flutter could be precipitated. For instance, in studying the Clark Y section, an investigation was first carried out for determining the angle of attack near the angle of zero lift at which flutter could be precipitated with a minimum velocity; and a similar investigation was carried out for obtaining this information for the angle of attack near that of the burble point. With these two angles determined, investigations were then carried out for determining a curve of critical air velocity at which flutter can be precipitated as a function of the torsional frequency of flutter of the airfoil. Similar investigations were performed on the four additional airfoils. These data are reported in Figures 3 and 4. Before discussing these curves, it should be noted that a careful investigation conducted in connection with these tests shows that the airfoils flutter in a frequency which is, for all practical purposes, the natural frequency of vibration in the mode of flutter, which, in these experiments, has proven to be almost a pure torsional flutter.

It may be noted in Figure 3, which contains the graphs for the angle of attack near that of zero lift, that the U. S. A. 35-A, the thick airfoil section with the flat lower surface, is very much more susceptible to wing flutter than are any of the other airfoil sections. For instance, a particular combination of torsional rigidity and mass distribution which will produce a natural torsional frequency of vibration of 600 cycles per minute will, for the U. S. A. 35-A indicate a critical air velocity of flutter precipitation at approximately 21 miles per hour, while in the case of any of the other airfoil sections, except for that of the perfectly streamlined section, we find that a speed of approximately 80 miles per hour is required to precipitate flutter. Since it was found that no flutter could be obtained on the perfectly streamlined airfoil section at the angle of zero lift, it is clear that the curves for the two thin sections may be expected to lie quite low with reference to the frequency of vibration since they approach the flat surface as a limit, it being apparent, of course, that the flat surface is also the limit of the perfectly streamlined section. The most interesting observation, however, which may be made in studying these curves is the large difference in flutter characteristics between the two thick airfoil sections, namely, the U. S. A. 35-A and the N. A. C. A. No. 81 root section. In flutter characteristics, the N. A. C. A. No. 81 root section compares favorably with the characteris-

tics of the thin airfoil sections and, with a reasonable degree of rigidity, which will, for instance, produce a natural frequency within the neighborhood of 900 to 1,000 per minute, flutter would be very difficult to obtain. It appears that this superiority of the N. A. C. A. No. 81 root section may be credited to the nearness of its approach to a perfectly symmetrical streamlined section. We conclude, therefore, in this case, that an airfoil which approaches a perfectly symmetrical streamlined section in cross-sectional characteristics will have advantageous wing flutter characteristics at the angle of attack near that of zero lift.

Turning now to Figure 4 for a study of the flutter characteristics of these four airfoils at an angle of attack near that of the burble point, we find that the cross section of the airfoil makes very little difference in the air velocity at which flutter is precipitated. It should be noted with reference to Figure 4 that these curves were obtained with the airfoils restrained to vibrate in torsion only. This restraint was necessary because the test structure was not sufficiently strong to withstand the very high lift loads at this large angle of attack. Other experiments, the results of which are not recorded here, however, showed that the influence of the restraint was not appreciable.

THE EFFECT OF THE LOCATION OF THE ELASTIC AXIS AND THE EFFECT OF THE DISTRIBUTION OF THE MASS OF THE AIRFOIL ON ITS FLUTTER CHARACTERISTICS

It was found from previous investigations and studies and confirmed by these experiments that the most influential physical characteristic of an airfoil upon its tendency to flutter is its natural frequency of torsional vibration. (In this connection, it should be noted that a cantilever wing will not vibrate freely or flutter in an air stream in pure torsion, but rather in a combination of torsion and bending except when the elastic axis coincides with the gravity axis of the wing. However, for the usual airfoil of this type, the true natural frequency in the combined mode will be very nearly the natural frequency in pure torsion.) In studying the effect of the location of the elastic axis and the mass distribution of the airfoil on its flutter characteristics, it behooves us not to lose sight of the effect these physical characteristics of the airfoil has on its natural frequency of vibration. For instance, we may conclude that a particular combination of elastic axis location and mass distribution is advantageous whereas it may be advantageous only because this particular combination produces a natural frequency which is advantageous. In studying these characteristics, therefore, the following method was adopted:

It was first assumed that a location of the elastic axis at 30 per cent of the chord from the leading edge, and the leading and trailing edges free from added weights to be the standard condition of test. The curves of critical air velocity of flutter as a function of the frequency of flutter previously discussed were accordingly taken as standard flutter characteristic curves for each of these airfoils. Data obtained for any other condition were then compared directly to these curves.

⁴See Air Corps Information Circular No. 635.

Figure 5 shows this comparison for the U. S. A. 35-A for an angle of attack near that of zero lift. It will be noted that the mass distribution and the location of the elastic axis has very little influence in materially lowering the frequency velocity characteristic curve for the airfoil. It is not apparent that even the slight distance noted is due to any cause other than experimental errors. It should be noted in passing that any irregularity in the operation of the wing flutter apparatus normally hinders fluttering, hence, the error is practically always such to make the airfoil appear advantageous; that is, any difficulty in the apparatus will tend to increase the velocity at which flutter is precipitated. It is probable that the comparative points depicting the influence of the mass distribution and location of the elastic axis represent the lowest velocity of flutter, but it is practically certain that the velocity of flutter in each case is no higher than represented. This statement may be made also for all frequency velocity curves; that is, that the lowest velocity points, in general, represent more nearly the actual characteristics.

Figure 6 shows the elastic axis location and mass distribution characteristics for the N. A. C. A. No. 81 root section airfoil, and Figures 7 and 8 show the corresponding characteristics respectively for the Clark Y airfoil and the N. A. C. A. M-6 airfoil.

It appears, in the case of each of these airfoils, that the mass distribution and the location of the elastic axis does not materially affect the characteristic frequency velocity curve of the airfoil. This, however, should not be taken as conclusive, but additional experiments of a similar nature should be made, preferably to obtain complete curves for each of the various conditions; these complete curves should be compared to the standard characteristic curve. This statement is especially true for those points which appear to represent a favorable condition.

THE EFFECT OF THE SIZE OF THE AIRFOIL

For the investigation of the effect of the size of an airfoil on its flutter characteristics the U. S. A. 35-A section was chosen. The three following sizes were used:

- 6 inches by 24 inches.
- 9 inches by 36 inches.
- 12 inches by 36 inches.

The size of the airfoils was limited by the size of the wind tunnel. The investigation was divided into two parts, namely, (a) that pertaining to the characteristics obtained for an angle of attack near that of zero lift and (b) that pertaining to the characteristics obtained for an angle of attack near that of the burble point. It should be remarked before entering the discussion of the characteristic curves pertaining to the effect of size, that it was very difficult to control exactly the angle of attack at which flutter was actually precipitated. For instance, if the airfoil were set at -13° , the angle may have been a degree or so off when flutter started. This discrepancy may be attributed to the disturbing effect of the air stream before flutter is actually precipitated. However, these data should not be taken too seriously in so far as actual magnitudes are concerned. The scale effect in these experiments is undoubtedly quite large. It is not, however, the quan-

titative data which the authors consider important, but rather the qualitative data, and the proposed method, illustrated by these experiments, of attacking the wing-flutter problem in a manner which will enable the engineer to design monoplane wings and also propeller blades to preclude flutter. The characteristic curves, however, have been graphed and other characteristic curves and formulas derived as though the data were not questionable quantitatively to, at least, encourage further research along the lines indicated.

The authors have assumed, after a careful study of the problem and the results of hundreds of experiments, that the critical velocity at which wing flutter is precipitated may be expressed by the formula

$$V = K f^n C^m$$

in which V is the critical velocity at which flutter is precipitated in feet per second, f is the natural frequency of torsional vibration of the airfoil in cycles per second, C is the chord of the airfoil in feet, and K is a constant which depends on the particular airfoil section, density of the air, etc.

Figure 9 shows the velocity frequency characteristic curves for the three sizes of the U. S. A. 35-A airfoil. The curves are graphed with velocity as a function of frequency. These data are also plotted as shown in Figure 10 on logarithmic paper for the purpose of obtaining the exponent n . With this exponent known, together with the coefficient k , defined in Figure 10, theoretical curves were drawn as indicated in Figure 9, which, as will be noted, fit the data with a fair degree of accuracy. It appears, however, from Figure 9 that considerable latitude may be taken in the choice of the exponent n .

To study the effect of size, points were taken from the curves in Figure 9 and plotted with air velocity as a function of the chord as shown in Figure 11. These derived data were also plotted on logarithmic paper as shown in Figure 12 for the purpose of obtaining the exponent m . It was accordingly found from these proceedings that the velocity at which flutter is precipitated is proportional to $f^{2.65}$ and to $C^{2.8}$, hence, as previously assumed,

$$V = K f^{2.65} C^{2.8}$$

The average value of K for this formula was obtained from Figure 9 as indicated in Table 1.

TABLE 1

$$K = \frac{V}{f^{2.65} C^{2.8}}$$

(C=0.5)			(C=0.75)			(C=1.00)		
K_1	f	V	K_2	f	V	K_3	f	V
0.0317	10	2.0	0.0394	10	7.0	0.0336	10	15.0
.0276	20	11.0	.0365	20	41.0	.0306	15	40.0
.0263	40	66.0	.0363	30	120.0	.0323	20	91.0

$$\text{Average } K = \frac{\Sigma K_1 + \Sigma K_2 + \Sigma K_3}{9}, K = 0.0327$$

Now, if these data were quantitatively correct, and the scale effect in predicting the behaviour of full-scale airfoils from model airfoils were negligible, then the formula as obtained could be used to determine the velocity at which flutter may be precipitated in a full-scale airfoil. As an example, the graph of Figure 13

is calculated for a U. S. A. 35-A airfoil with an 8-foot chord. It is obvious, of course, that we must be able to calculate the natural frequency of torsional oscillations of such a wing. It has been shown,⁵ however, that this can be readily calculated at the expense of only a small amount of labor, from the design drawings, before a movement is made in the construction of the actual wing.

The critical velocity of airfoil flutter at an angle of attack near that of the burble point, it is assumed, may also be expressed by the formula.

$$V = K^n f C^m$$

The values of K , n , and m , of course, will be different from those values determined for the angle of attack near that of zero lift. We find from velocity-frequency characteristic curves of Figure 14, by inspection, that the exponent n is one. The exponent m as evaluated in Figures 15 and 16 was found to be 1.39. Unfortunately, however, the data for this condition is not of a very good quality. The experiments should be repeated.

Evaluating K in the manner previously described in connection with the low-angle-of-attack condition, we find, as noted in Table II, that K is 7.04. The complete formula accordingly is

$$V = 7.04 f C^{1.39}$$

TABLE 2

$$K = \frac{V}{f C^{1.39}}$$

C	$C^{1.39}$	f	V	K
0.50	0.3800	25	67	7.05
0.75	0.6760	25	117	6.94
1.00	1.0000	15	107	7.13

Average $K = 7.04$.

Projecting this result to a full-scale wing with a chord of 8 feet, we obtain the frequency velocity curve of Figure 17.

It is apparent that when sufficient experiment investigations have been carried out so that curves of the nature of those in Figures 13 and 17 may be obtained, representing the actual condition, it will not be difficult to design a monoplane wing to preclude wing flutter below a specified velocity. It appears, also, that a procedure of this nature may be conveniently used in systematically investigating propeller flutter.

GENERAL SUMMARY

The data collected during the course of the experiments described above were supplemented, and to a large extent, corroborated by a parallel study of most of the available literature on the subject—German, Dutch, and English. Certain recommendations of Messrs. R. A. Frazer and W. J. Duncan contained in their book, *The Flutter of Aeroplane Wings*, have been abstracted and are included in this report as Appendix No. 2.

⁵ See "Simple Approximate Method of Determining the Natural Frequency of Torsional Vibration. (With Particular Reference to Monoplane Wings and Propeller Blades), Airplane Department Memorandum No. 1062, 17 pages, May 24, 1929, Matériel Division, Air Corps, Wright Field." "The Calculation of the Natural Frequency of a Cantilever Monoplane Wing," by S. R. Carpenter, Airplane Department Memorandum No. 1064, Matériel Division, Air Corps, Wright Field.

CONCLUSIONS

From the study and experiments described above, it is possible to define certain important features that must be considered in the design of cantilevered monoplane wings intended for high performances.

1. *Ailerons*, should be of small moment of inertia about hinges, and be statically balanced about the hinge line. The control hook-up should have a minimum of elastic or flexible elements. Push and pull rods with bell cranks, etc., are recommended. For large installations or extremely high speeds an irreversible hook-up may be desirable or even necessary.

2. *Torsional rigidity*.—No property of the wing appears to have a more clear-cut relation to the flutter characteristics than the natural period of the wing in torsion. The natural period for a wing of given size and mass being directly proportional to the torsional rigidity of the wing, this latter property in itself is considered as being the one to have the greatest direct bearing on the flutter characteristics. The most direct and satisfactory method of obtaining increased torsional rigidity appears to be by employing a continuous rigid outer covering of wood or metal. Apparently, several other considerations affecting high-speed wing design also dictate the same measures as those required for satisfactory torsional rigidity. These others are, (a) limitations of fabric as a covering from a standpoint of local strength, (b) desirability of incorporating the drag system in the covering.

3. *Airfoil section*.—Both the numerical results and the visual evidence of air flow point clearly to the desirability of choosing an airfoil covering closest to a stream-line section. The N. A. C. A. 81 with its downward under camber had markedly less tendency toward high speed flutter than a wing of equivalent depth—U. S. A. 35A. This indicates the desirability of further study of airfoils designed for high speed operation, and in particular, the application of the evidence of this investigation to the development of more stable propeller blades.

4. *Effect of the location of the elastic axis*, and

5. *The effect of the distribution of the mass of the airfoil*.—In the above experiments very little variation in the flutter characteristics of these airfoils could be induced by relatively large changes in the positions of the above axis and mass. Therefore, it was assumed, inasmuch as in a well designed wing the possible variation is much smaller than that investigated above, that the position of the elastic axis and the mass distribution of the wing would take positions sufficiently close together so as not to require any consideration connected with flutter stability. However, the necessity is emphasized for avoiding mass concentrations in the trailing edge or rearward portion of the wing, particularly in the outboard or tip portions. Aileron parts, attachments and controls, and landing lights must be scrutinized for excess weight and optimum location. The effect of outboard pusher engines supported under the rear of the wing would require careful consideration.

6. *The effect of the size of the airfoil*.—The experimental investigation should be extended to airfoils of much larger size than those used, in order to accurately evaluate effects of size. The foregoing data indicate the lines along which a more accurate investigation quantitatively might be carried out.

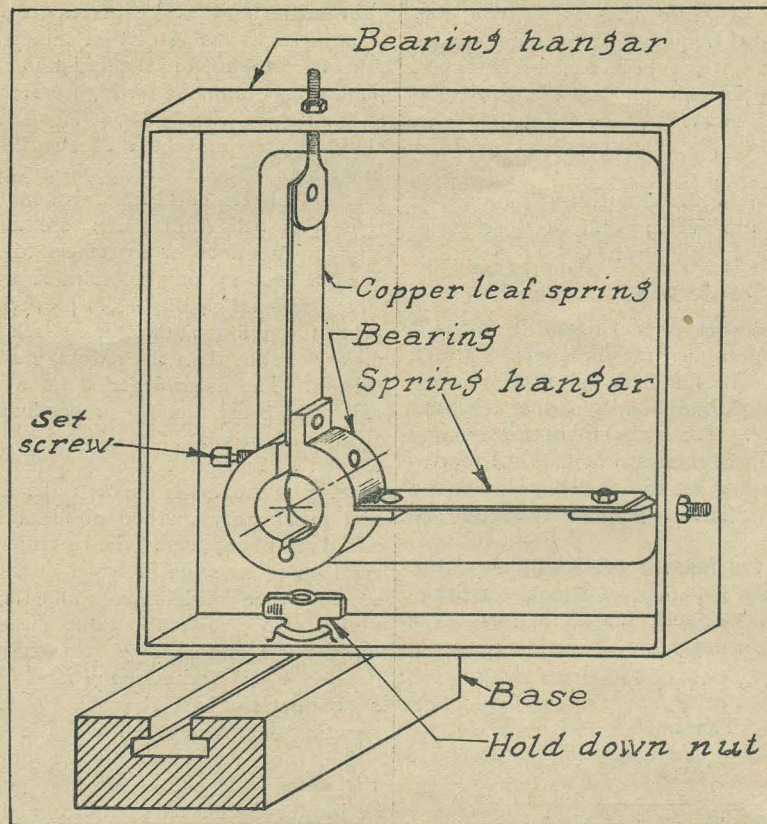


FIGURE 1.—Frictionless bearing

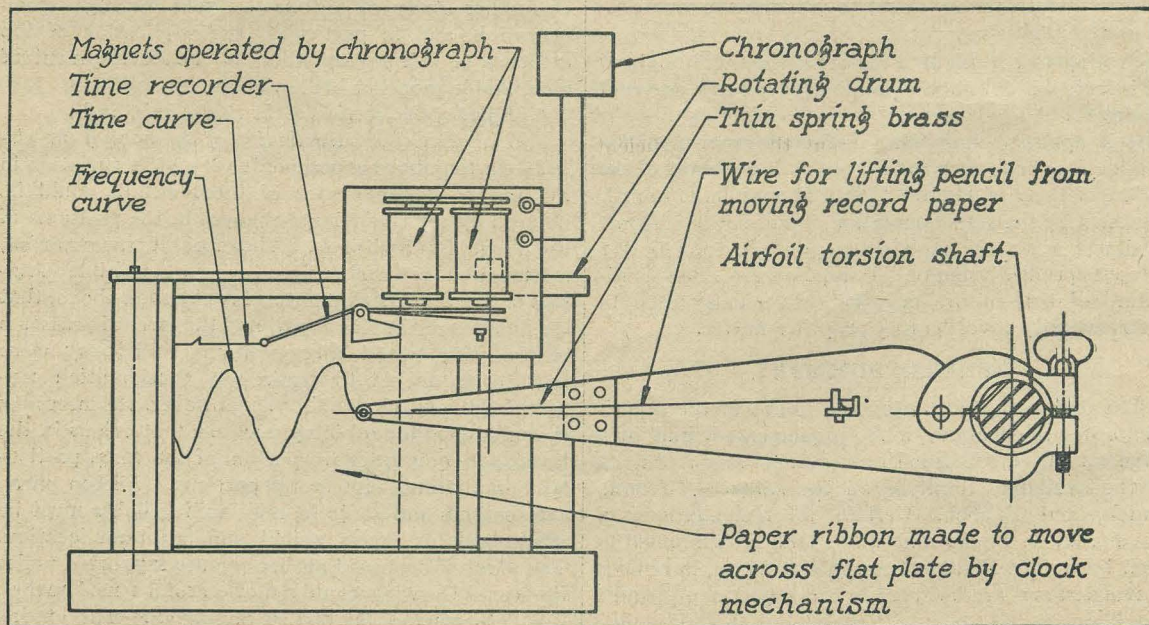


FIGURE 2.—Airfoil frequency recorder

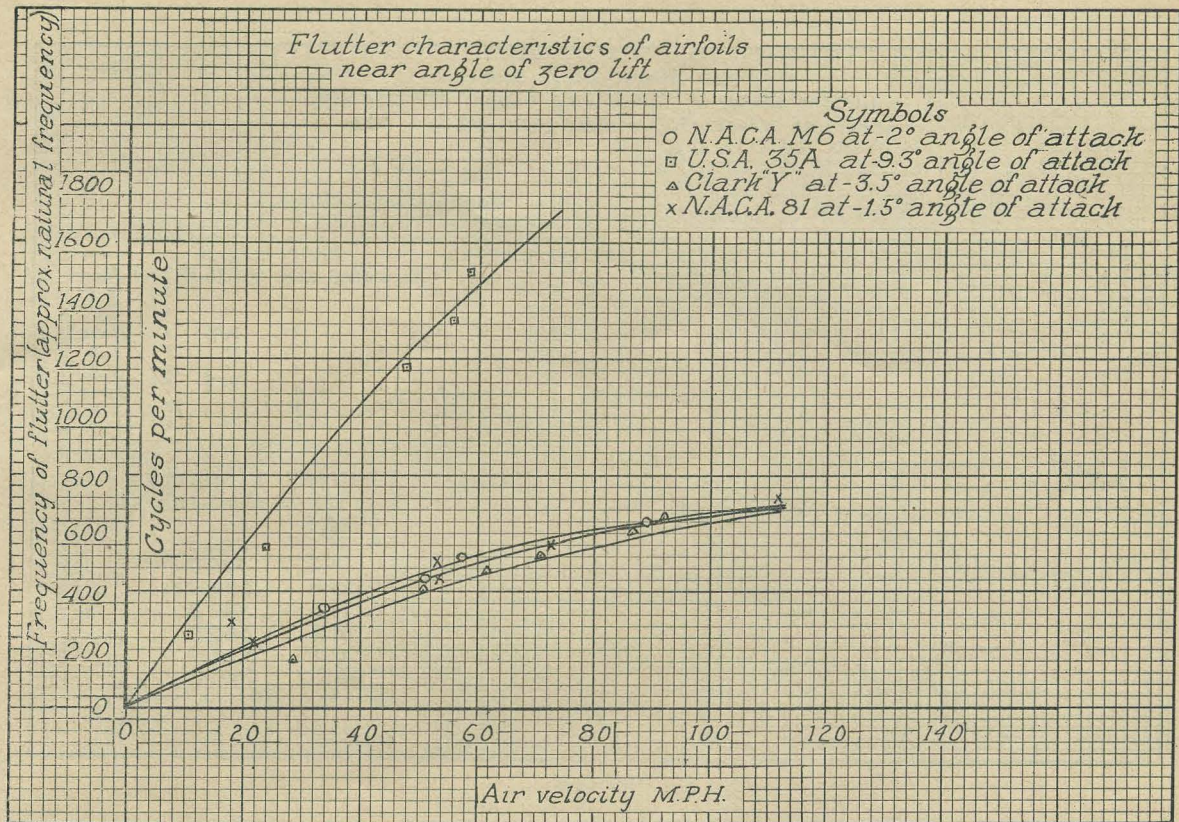


FIGURE 3

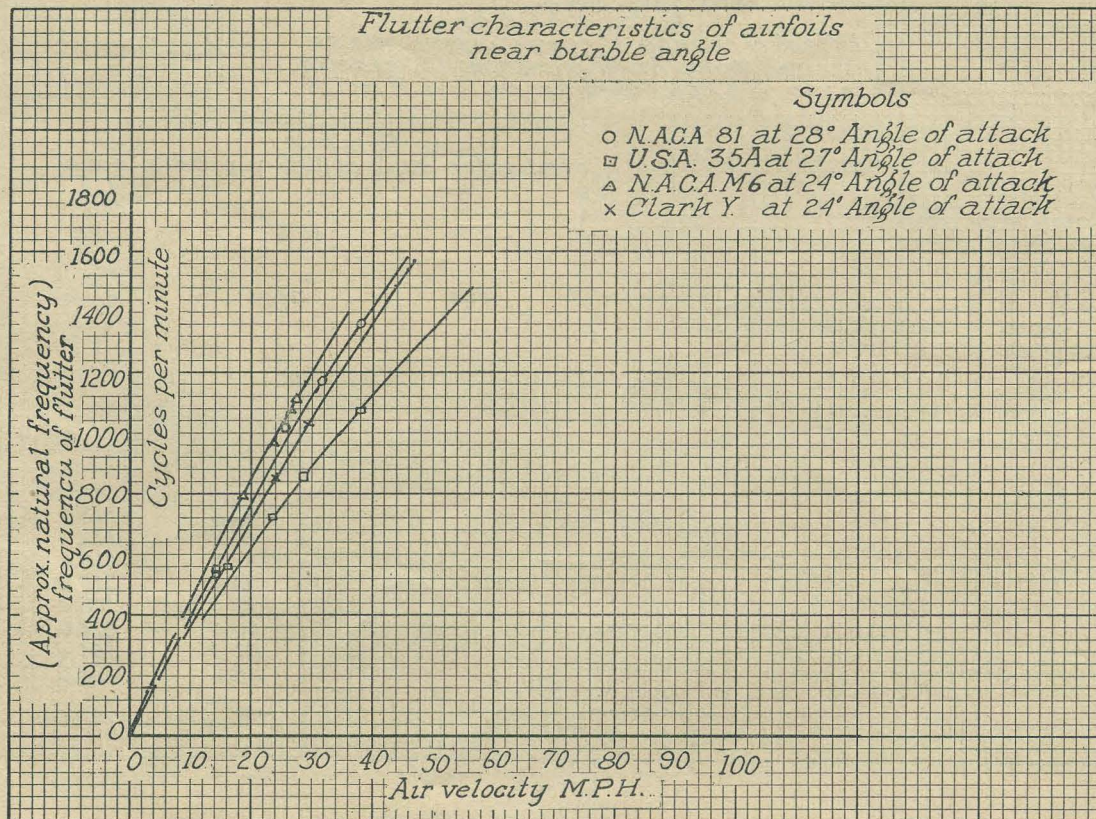


FIGURE 4

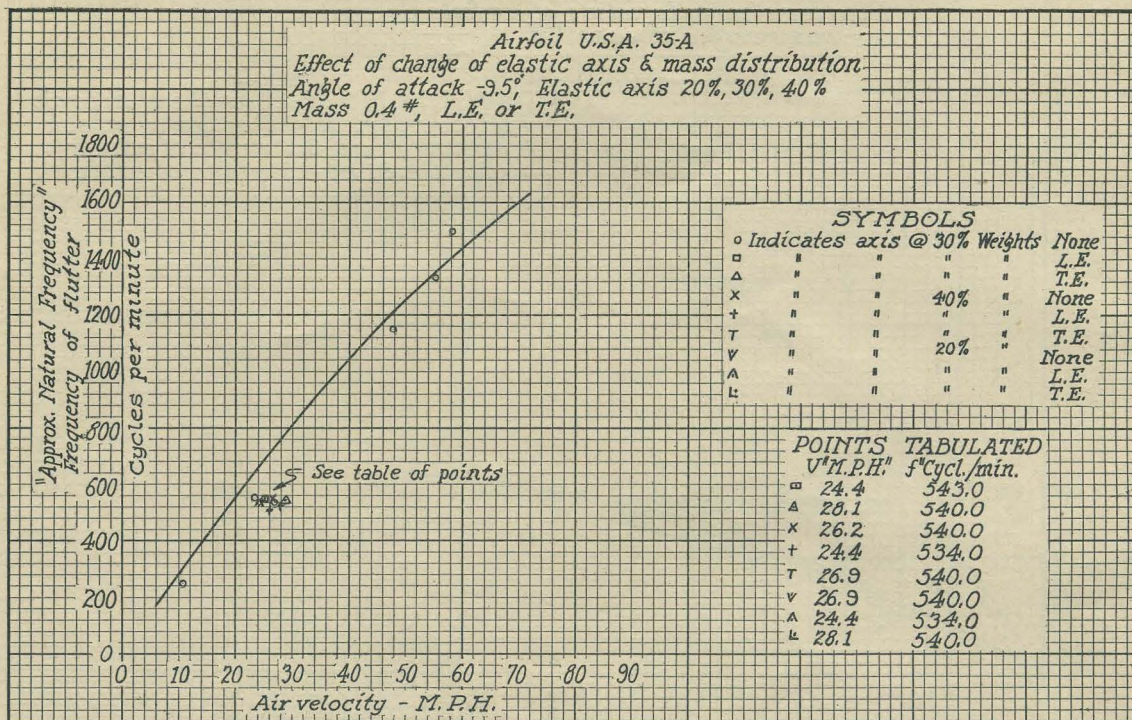


FIGURE 5

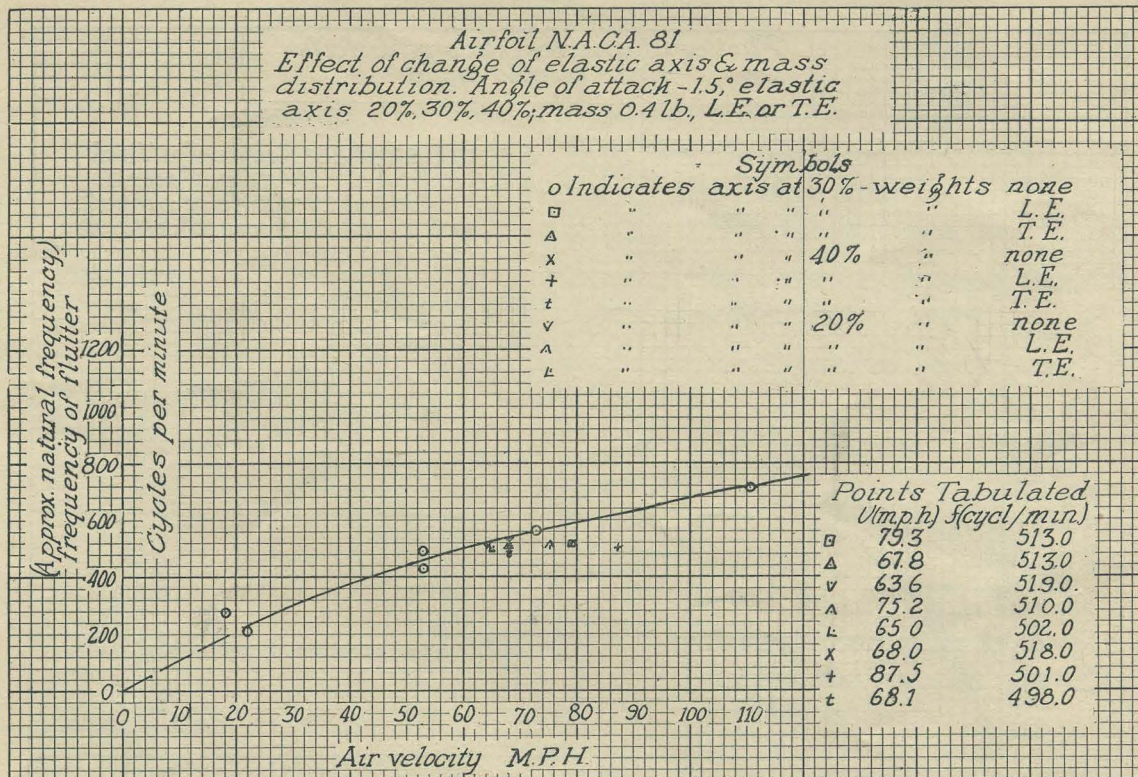


FIGURE 6

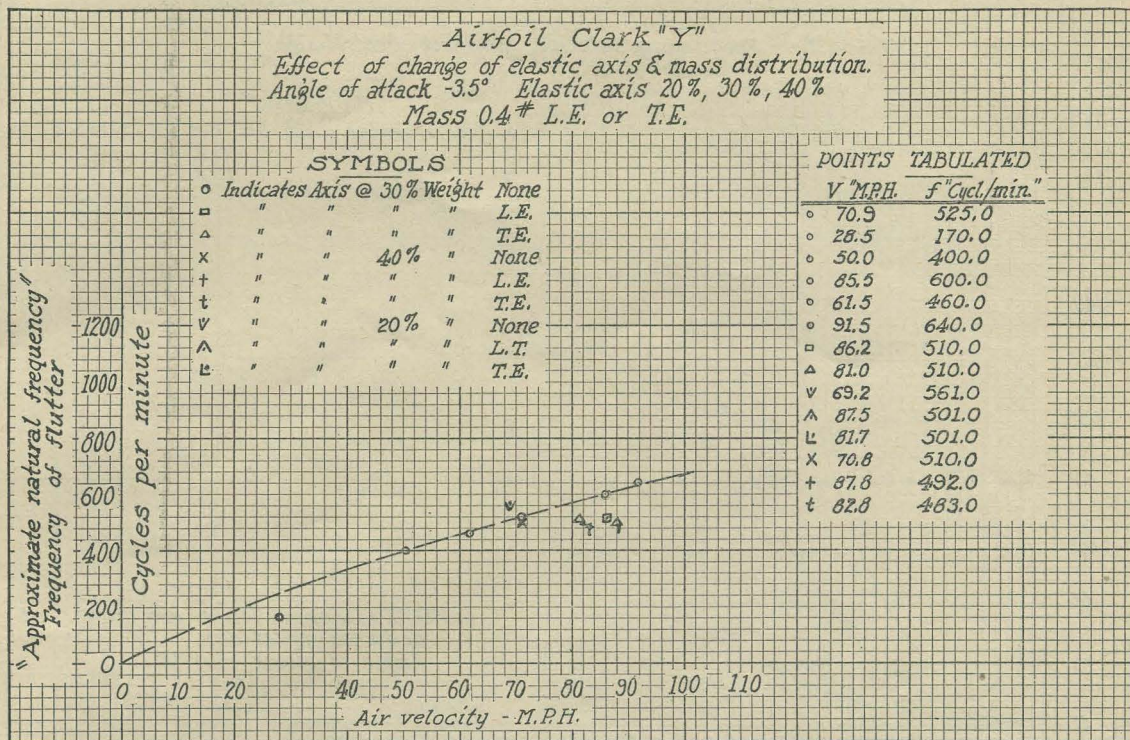


FIGURE 7

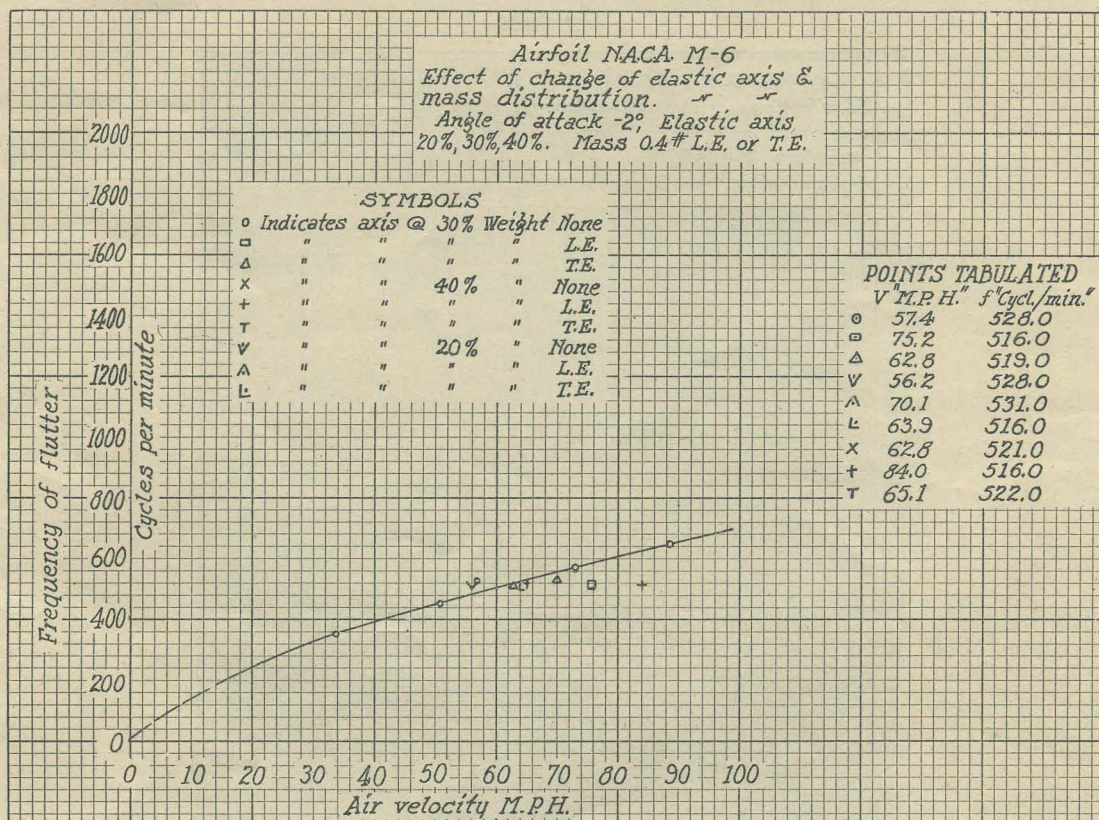


FIGURE 8

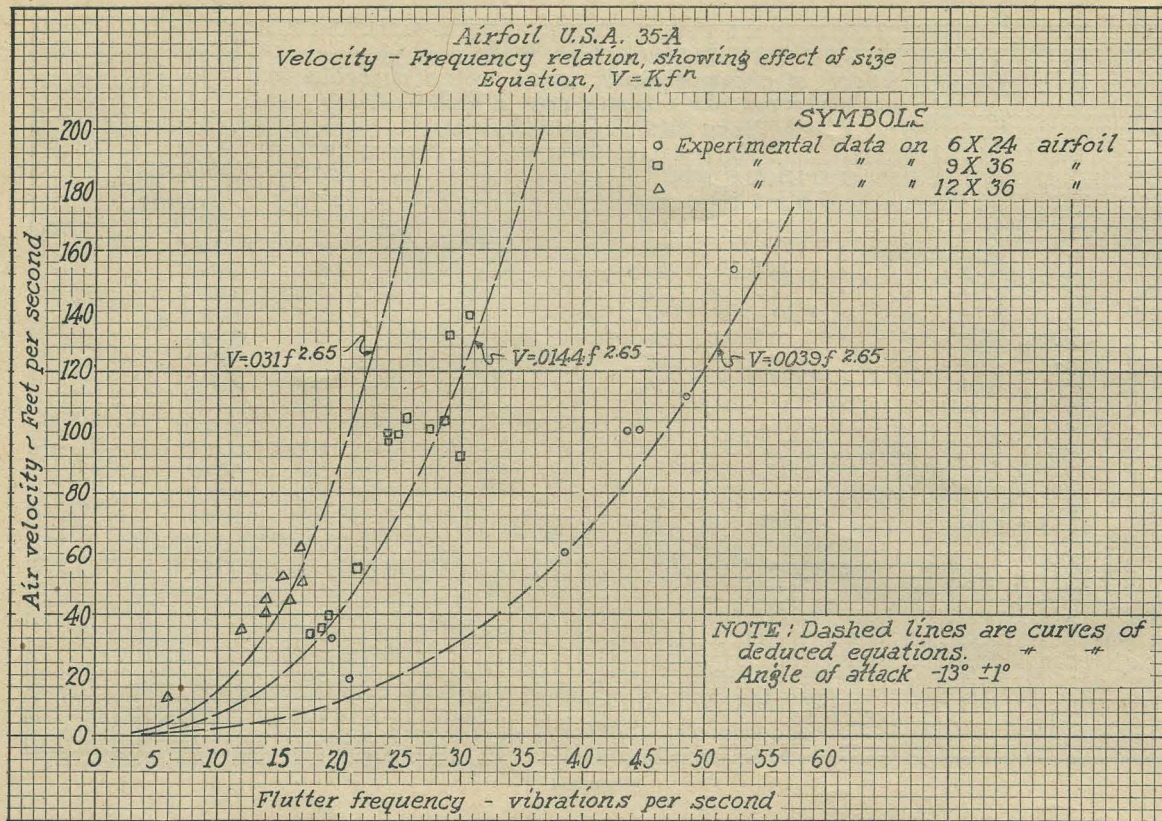


FIGURE 9

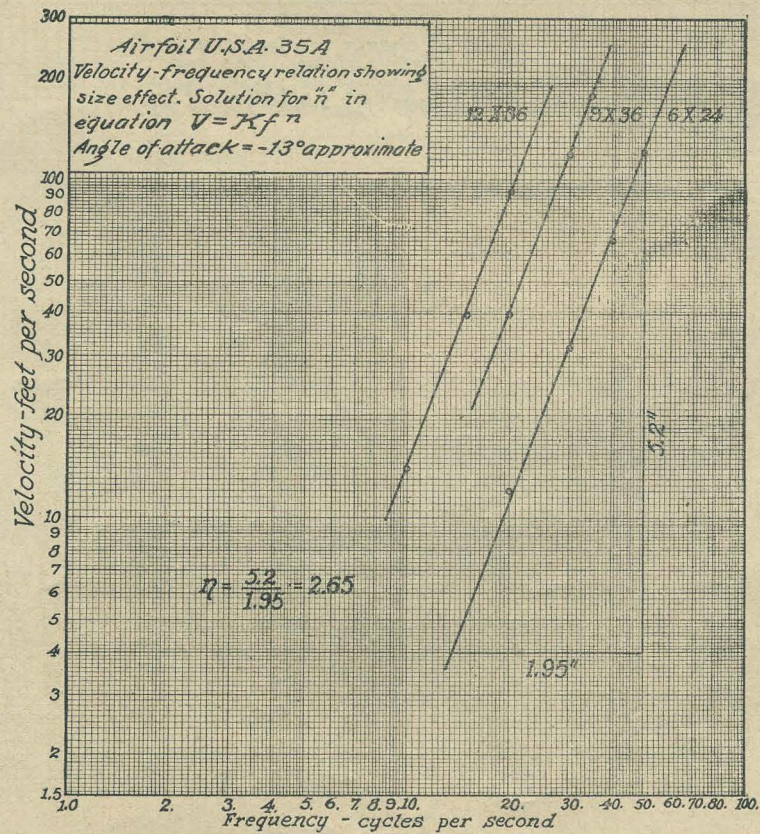


FIGURE 10

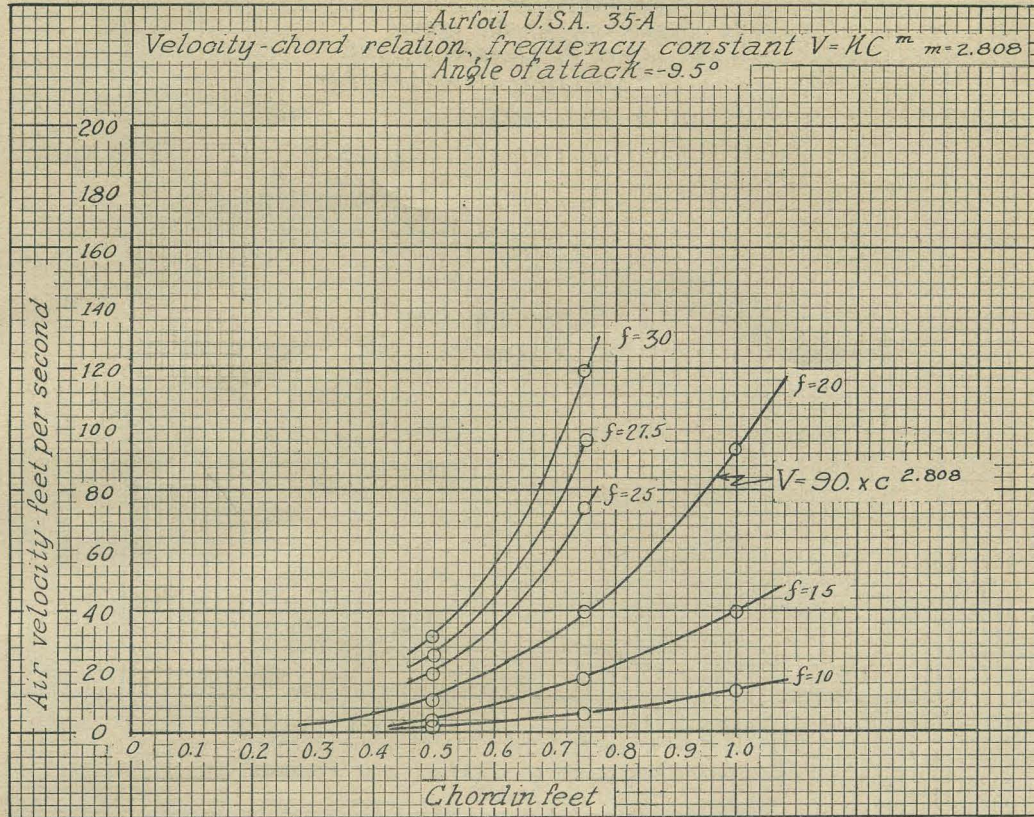


FIGURE 11

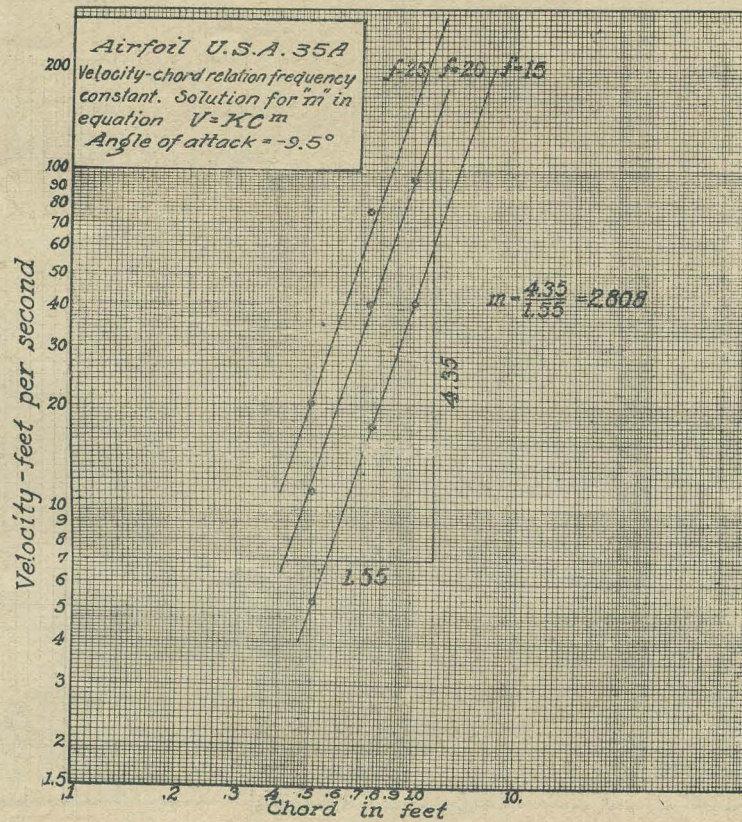


FIGURE 12

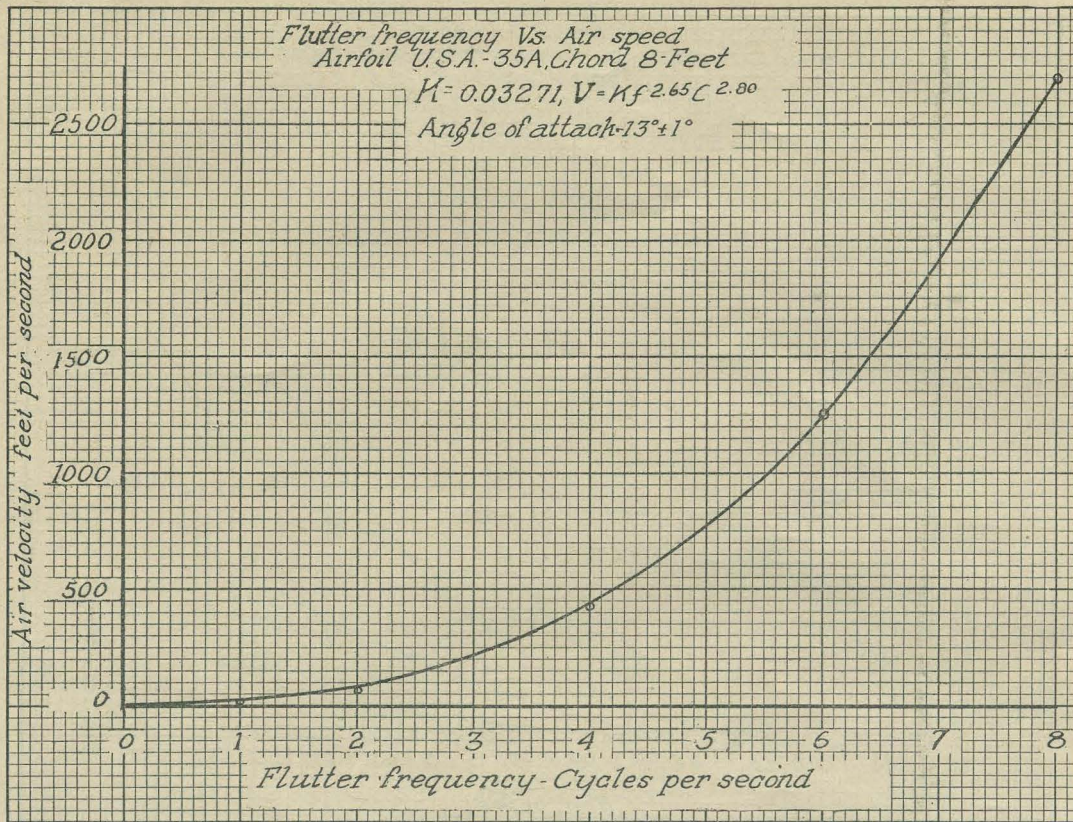


FIGURE 13

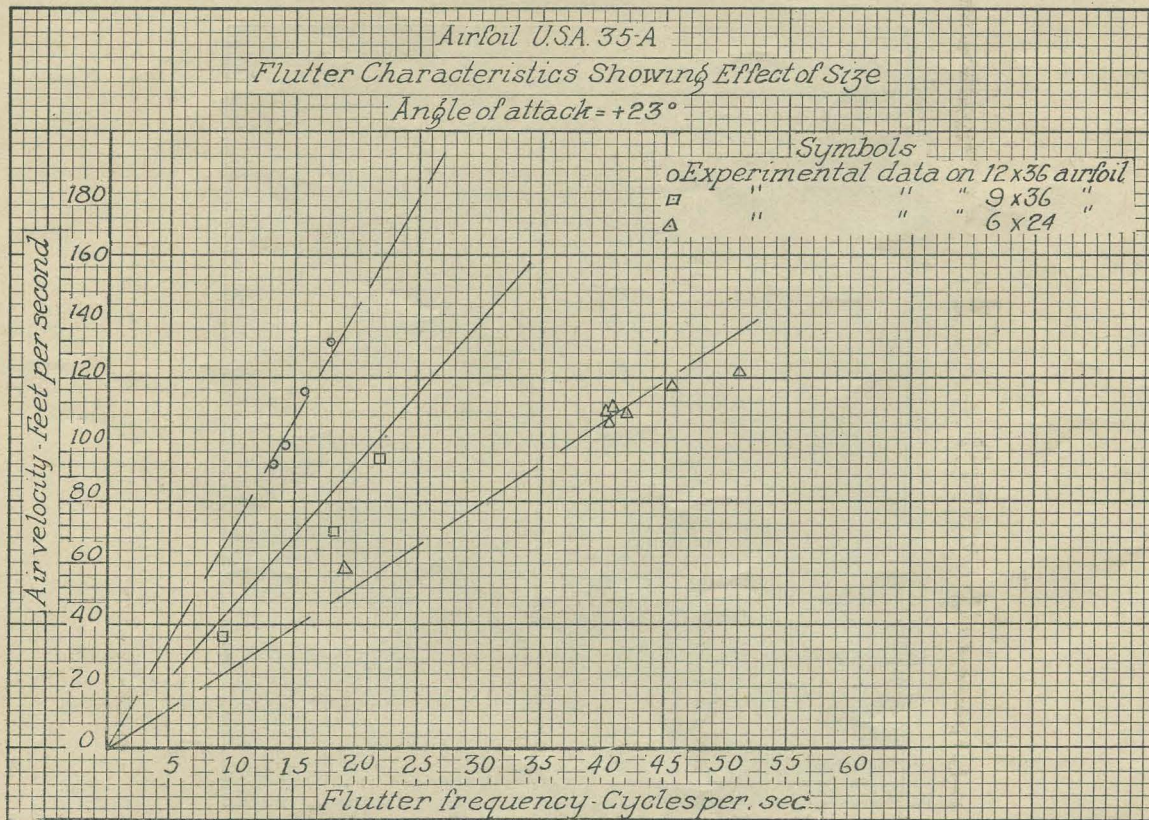


FIGURE 14

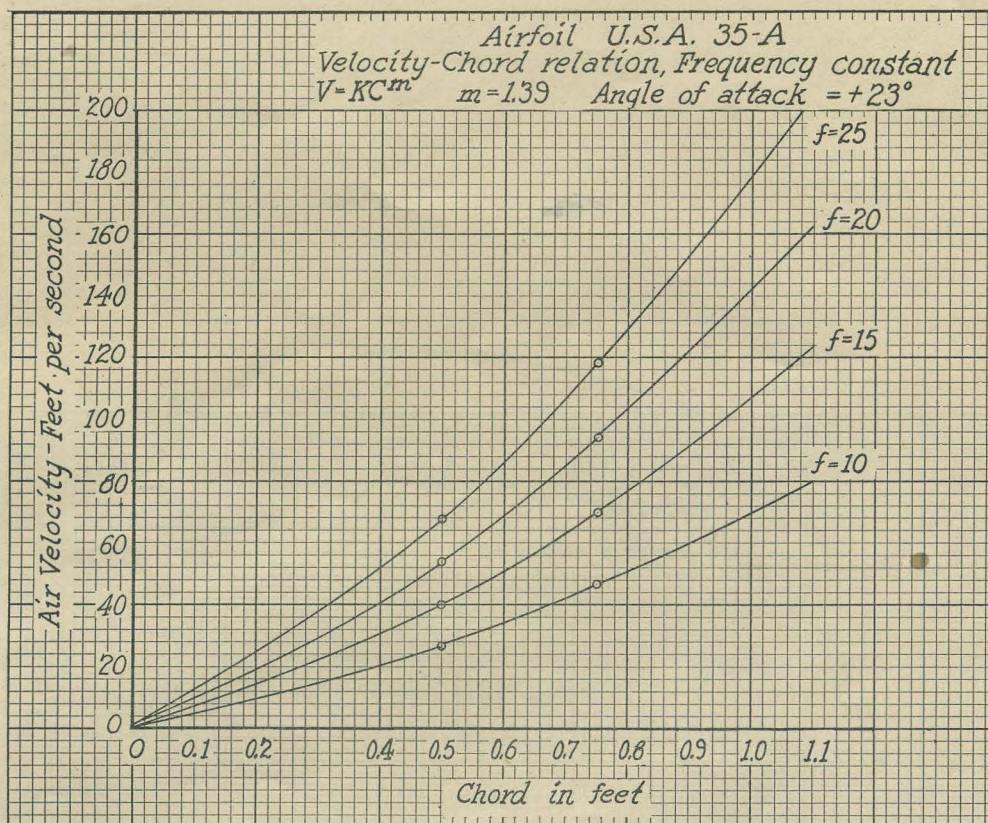


FIGURE 15

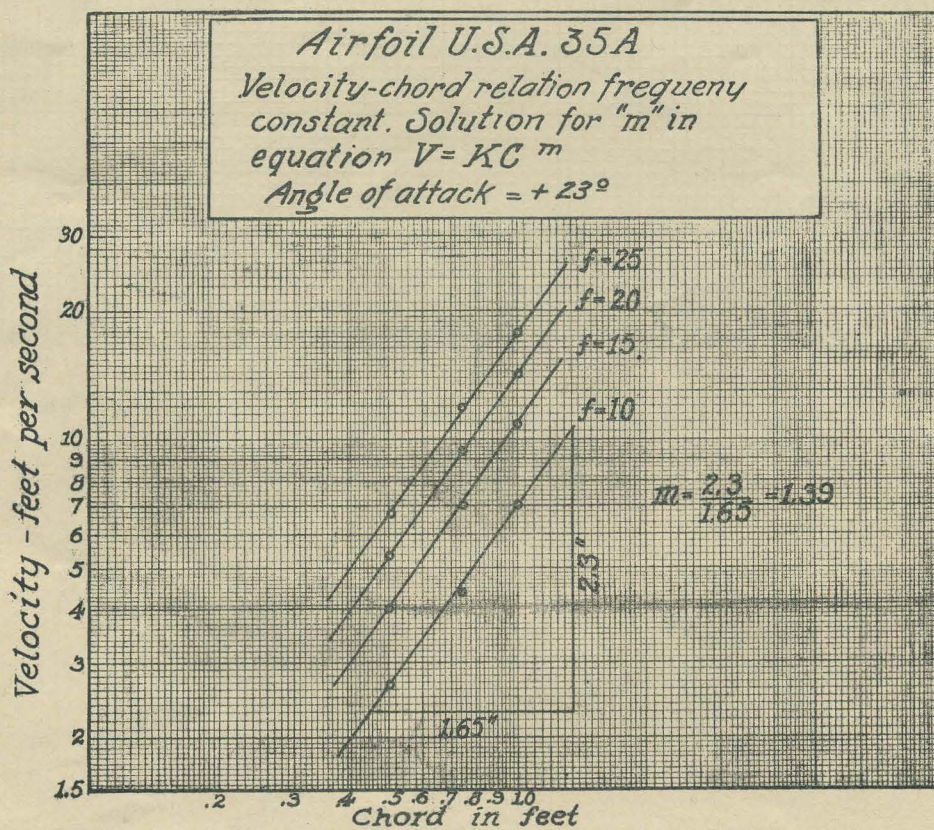


FIGURE 16

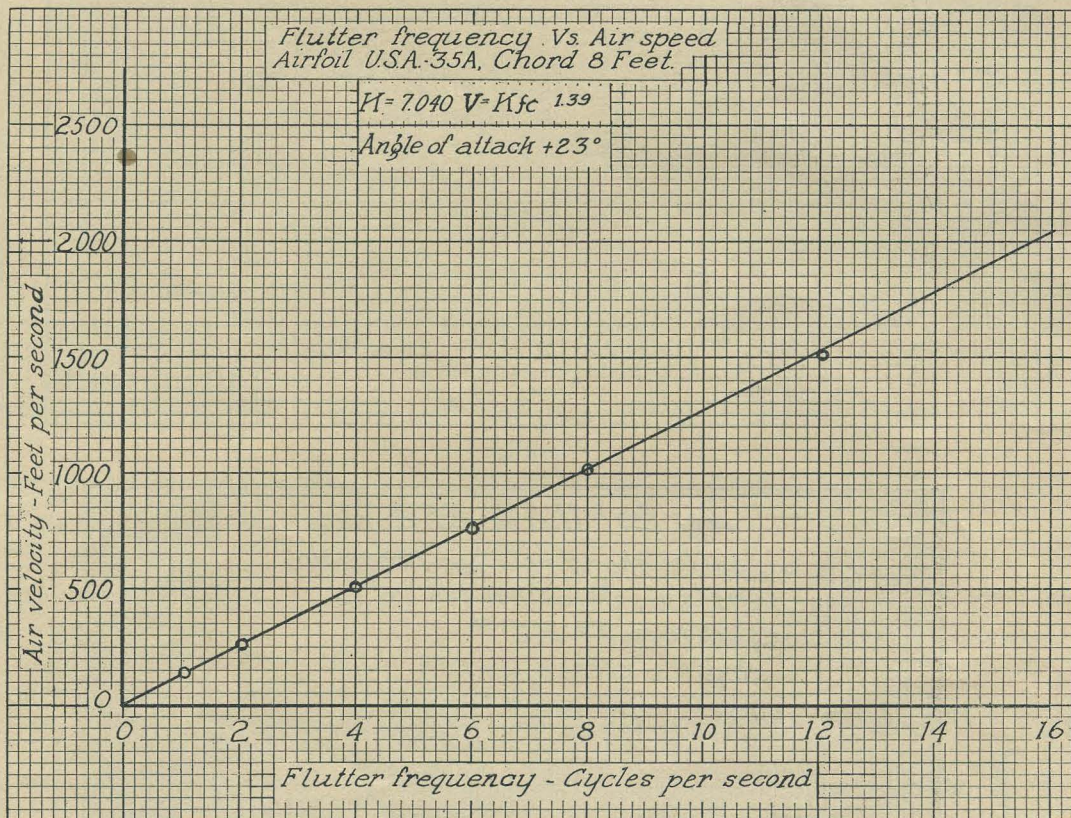


FIGURE 17

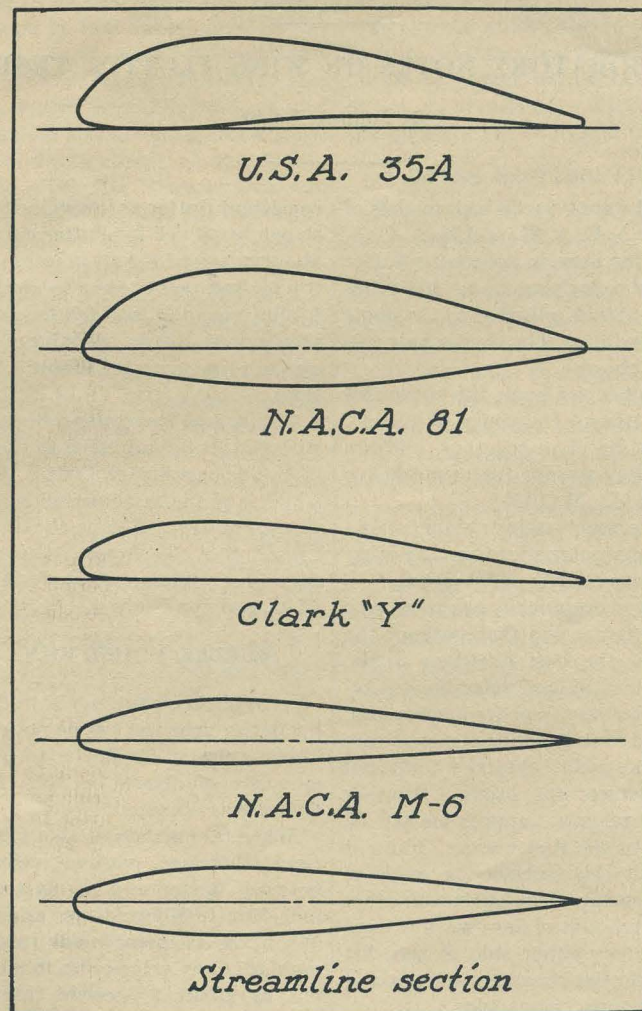


FIGURE 18

APPENDIX NO. 1
TO
AIRFOIL FLUTTER INVESTIGATION
A. D. M. 1075

LABORATORY NOTES ON WING FLUTTER TESTS

By John A. Edgar

The wing sections tested were 9 by 36 inch models of Clark Y, U. S. A. 35-A, N. A. C. A. 81, and N. A. C. A. M-6. The tests made so far were to determine flutter frequency at various wind velocities up to 100 miles per hour with the angle of attack adjusted to the angle of zero lift as nearly as possible. The elastic axis was kept at 30 per cent of the chord.

At velocities above 50 miles per hour, the curves for all sections (velocity of flutter vs. frequency of flutter), except the U. S. A. 35-A, lie close together, and are almost straight lines, bending toward the origin below 50 miles per hour. (See A. D. M. 1075.)

The U. S. A. 35-A has a much steeper slope, shows wide differences in flutter characteristics from the other sections, and will be investigated in more detail.

The N. A. C. A. 81 showed a tendency to droop very steeply toward the origin, indicating that perhaps the angle of zero lift was not the best fluttering angle. (This would be most evident at low velocities.) Accordingly, the section was tested at low frequency, and, therefore, low velocity, and found to flutter most freely at $+45^\circ$ attack. Also, the point obtained indicated that the curve should intersect the origin. Another point obtained at higher velocity (approximately 55 miles per hour) fell close to the first curve. Thus, it may be concluded that for this section, the angle of maximum flutter is more sharply defined than in other sections. From the small amount of data we now have it appears that a few degrees either side of zero lift makes little change in the flutter characteristics except at low velocities and, therefore, frequencies.

The peculiar behavior of the U. S. A. 35-A may be due to its thickness. The fact that the N. A. C. A. 81 showed almost the same characteristics as the thin sections indicates that possibly the negative camber of the N. A. C. A. 81 makes it equivalent to the thinner sections as far as flutter is concerned.

FURTHER TESTS OF U. S. A. 35-A.

At low angles (less than -8.5°) the wing showed a flutter tendency at velocities around 13 miles per hour, but the torsional flutter was damped out by excessive bending. For these runs, the natural period is kept constant at about 240 cycles per minute. The most

consistent flutter at low velocity was at about -9.5° as shown by $\propto$ vel. for flutter curve where the period was about constant for all points.

The first point taken to check the first curve was at 1,160 frequency, and fell below the first curve. Other points were taken, defining a new curve, which is a straight line from the origin. This led to two observations:

1. The real frequency-velocity curve is the one taken with the air foil adjusted to the best fluttering angle.

2. The best flutter angle is that which yields a flutter which is of the same period as the natural frequency of the apparatus. This is shown in the data for the second U. S. A. 35-A test. Just why the U. S. A. 35-A curve is so different from the Clark Y, the N. A. C. A. M-6, and the N. A. C. A. 81 is not yet clear.

BURBLE POINT RUNS OF U. S. A. 35-A

Several runs were made to determine the best angle for flutter near the burble point. The curve shows the lowest velocity for flutter to be 14.1 miles per hour at an angle of attack of 27° . Above 27° no sustained flutter was obtained.

When taking data at about 26° at various frequencies (and, therefore, various velocities) sharp definition between flutter and no flutter was found up to and including 1,080 cycles per minute at 38 miles per hour. When the frequency was raised, the flutter was not regular at any velocity up to 80 miles per hour, damping out at about $2\frac{1}{2}$ -second intervals. This may be a characteristic of the airfoil, but is more probably due to resonance of the restraining wires, or to flutter in bending. Test was concluded here. The frequency-velocity curve is practically a straight line through the origin. (See A. D. M. 1075.)

TEST OF CLARK Y NEAR BURBLE POINT

Procedure was as before. Above 22° there was no sustained flutter. Best flutter was at 20° to 22° and the test was run at 20° . Damping was serious as before above 30 miles per hour and 1,020 cycles per minute. A 1-pound weight hung on the drag wire eliminated some of the damping, allowing a reading at

40 miles per hour and 1,185 cycles per minute; however, 40 miles per hour appears high. It seems, therefore, that near the burble point flutter tends to disappear at high velocities.

The curve for the Clark Y is a straight line through the origin and has a slightly steeper slope than the U. S. A. 35-A.

During the test of the N. A. C. A. M-6 the old data on the 9 by 36, 6 by 24, and 12 by 36 U. S. A. 35-A wings were plotted. The curves did not look right. On examining the vibrograph strips, it was found that damping had occurred at all of the higher frequencies, indicating a condition such as that experienced in the later burble point runs, as already noted. There were not enough points in the lower frequencies to give any good indication of the flutter characteristics of the sections, and to show whether size made any difference.

In the "angle of best flutter test" of the N. A. C. A. M-6 (near burble), a peculiar characteristic was shown. At the outset, it was found that the frequency for a given velocity was higher than for the Clark Y or the U. S. A. 35-A. Then it was found that some flutter could be recorded at 69.4 miles per hour at 14° angle of attack, while at 14° to 30° the section fluttered freely at 790 cycles per minute at air speeds below 25 miles per hour. Then, at 32° the last point of flutter was obtained. This broad band of angular settings for pronounced flutter does not seem to be a desirable characteristic. It seems possible that the low C. P. travel of the M-6 may be the characteristic controlling this feature. As the run progressed, it was found that steady flutter was hard to obtain, being found only in the range between 800 cycles per minute and 1,080 cycles per minute at 18.5 and 21.5 miles per hour (setting 24°). Frequencies below 800 apparently were obtainable below the lowest tunnel velocity, while a point was roughly obtained between 1,300 and 1,600 cycles per minute at about 35 miles per hour. Ex-

cessive damping and an apparent forced frequency caused this point to be discarded.

TEST OF N. A. C. A. 81

In the run to find the angle of best flutter for this section, it was found that flutter at 34° occurred at 525 cycles per minute at a velocity below that of the tunnel minimum. The natural frequency was increased to 750 cycles per minute and the angle run remade. The best angle was found to be 28° , when flutter at 759 cycles per minute occurred at 19.5 miles per hour.

In the run at 28° , the N. A. C. A. 81 curve appeared to be a straight line through the origin, and showed flutter at higher frequencies and velocities than any of the other sections. The slope of the curve is about the mean of the M-6 and Clark Y.

MASS DISTRIBUTION TEST OF M-6

Two points on the N. A. C. A. 81 frequency-velocity curve (at 28°) were checked with the 0.4 pound mass placed first in the leading edge, then in the trailing edge. The mass seemed to affect the natural frequency, but as the velocity was correspondingly affected, the points fell very near the first curve. It is, therefore, tentatively concluded that the distribution of mass has no effect on the frequency-velocity characteristics of the wing at high angles of attack.

A similar check and conclusion was reached by obtaining two mass distribution points on the N. A. C. A. 81 at a low angle of attack, -1.5° . On further runs, both the mass distribution and the elastic axis position were changed. This introduction of more than one variable at a time does not seem to be sound experimental practice so early in the investigation. However, none of the points fell wide of the original curve.

The same type of runs were made on the N. A. C. A. M-6 with the same results.

APPENDIX NO. 2
TO
AIRFOIL FLUTTER INVESTIGATION
A. D. M. 1075

Abstract of Recommendations
FROM
"THE FLUTTER OF AEROPLANE WINGS"
By R. A. Frazer and W. J. Duncan

The following abstracts from the book of Messrs. R. A. Frazer and W. J. Duncan, *The Flutter of Aeroplane Wings*, are appended to this report for the reason that the conclusions arrived at by these authors agree very closely with the conclusions and recommendations derived from the Wright Field study and experiments.

The English authors use the term "axis of independence," which will be recognized as the theoretical axis about which angular movement of the airfoil produces zero change in wing moment. Whether this axis can be assumed to be located at the same point in a rapidly oscillating airfoil as in an airfoil tested in successive positions is open to doubt. However, such an axis of zero change of moment undoubtedly exists for every airfoil, and in dealing with this point it was assumed that this axis would lie substantially in the neighborhood of the axis experimentally located.

GROUP I. RECOMMENDATIONS RELATIVE TO AILERONS

(a) *Irreversibility of aileron control.*—The intention of this recommendation is that when the ailerons have been set at any desired angle, they shall remain locked to the wing in that position until again purposely moved by the pilot. The gear between each aileron and its automatic lock should be stiff and free from backlash. Such a system of control will clearly prevent all types of flutter involving motion of the ailerons relative to the wings.

Failing (a)—

(b) *Center of gravity of aileron slightly ahead of hinge.*—This could be met in various ways. For instance, by withdrawal of the hinge from the leading edge of the aileron and concentration of the mass forward; or, alternatively, by retention of the forward position of the hinge and recourse to some type of counterpoise or balancing plane. The latter method may prove inconsistent with items (c) or (f). It is desirable that the mass of the aileron should be distributed along its span as uniformly as possible. The use of a counterpoise at one end only of the aileron may be quite unsatisfactory, inasmuch as the inertial couplings (products of inertia) may then be large.

When an interaileron strut is in use, its mass should be viewed as evenly divided between the two ailerons so connected.

(c) *Moment of inertia of aileron small.*—In the interpretation of this recommendation it should be remembered that all the parts of the control system which move with the ailerons contribute effectively to the aileron moment of inertia. Thus, all such moving parts should be kept as light as possible.

(d) *An appreciable part, preferably rather more than one-half, of the aileron should lie inboard of the center line of the attachments of the outermost external wing bracing.*—The adoption of this measure is strongly advised, since it materially assists to minimize the couplings between the motions of the aileron and of the wing.

(e) *Aileron heavily damped; that is, artificially.*—The motion which is to be heavily damped is that of the aileron relative to the wing. An artificial damping device, if employed, should be of the fluid friction type. The use of solid friction is viewed as objectionable.

(f) *Aileron definitely underbalanced aerodynamically.*—A close approach to the condition of aerodynamical balance is considered undesirable, but the definition of the optimum position of the hinge is a matter for further systematic wind-tunnel research. It may, however, be stated that flutter tests on a number of different model wings suggest that a hinge placed at about 0.2 aileron chord from the aileron leading edge would prove satisfactory.

GROUP II. RECOMMENDATIONS RELATIVE TO WING STRUCTURES. WITH SPECIAL REFERENCE TO OVERHANGS

(g) *Balance of masses of each overhang (including corresponding portion of aileron) about its flexural axis.*—The object of this recommendation is to eliminate the inertial coupling between the flexural and torsional motions of the whole wing (in the case of monoplanes), or of each overhang (in the case of biplanes). As explained elsewhere this particular coupling can be eliminated by distribution of the wing

masses in such a manner that the flexural torsional product of inertia (as defined in par. 6 (a)) vanishes. A balance of the masses in each section about the flexural axis appears to be the simplest method of effecting the required result. Some tolerance is allowable, but the center of mass should be forward, rather than aft, of the flexural axis (see par. 63 (c)).

(h) *Flexural axis close to axis of independence.*—The aerodynamical coupling which disappears for the "axis of independence" is the rate of change of torsional moment due to the flexural velocity of the wing (see par. 6 (c), item (iv)). Strip theory suggests that this axis will lie at about one-quarter chord from the leading edge, but measurements on a model indicate that for a cantilever wing the true position is at about 0.3 chord from the leading edge (see par. 9 (a), item (h), and par. 54). In the present state of knowledge, the position of the axis of independence can not be viewed as controllable by the designer; thus, for suppression of the couplings, the practical procedure would be to adjust the positions of the flexural axis and of the principal axis of inertia so that they fall at the axis of independence. This has for its aim the sup-

pression of one of the aerodynamical couplings between the flexural and torsional motions of the wing (or overhang). The precise location of the axis of independence is likely to depend upon a number of factors such as wing section, shape of wing tip, and aspect ratio of overhang. Its position has hitherto only been determined for a wing of thin unsymmetrical section, with square tip and of aspect ratio 3. In this case it was found to lie at about 0.3 chord from the leading edge. If in the future the necessity should arise for particular attention to the measure, further wind-tunnel experiments would be desirable.

(j) *All elastic stiffnesses as large as possible.*—As already pointed out a proportional increase of all elastic stiffnesses would secure an elevation of the critical flutter speed. On the other hand, an increase of a single stiffness may in some cases actually be detrimental. Thus, if stiffening be adopted as a practical remedy for flutter, the safest procedure—in the absence of a special investigation on the particular machine involved—is to aim at an all-round stiffening, rather than at reinforcement of particular members.



